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Cenozoic erosion of the Scottish Highlands – Orkney – Shetland area: implications for uplift and previous sediment cover

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The Scottish Highlands are both an ancient mountain belt and, more recently, part of a passive continental margin – both features where the long term controls on topography are uncertain. During the Mesozoic the area may have been either a net sediment source, or at least in parts a net sediment sink. Balancing preserved sediment volumes in surrounding basins with the paleo-surface area of the Highlands exposed to erosion suggests that c. 2000 – 2400 m average thickness of (zero porosity) rock have been eroded from the Highlands in the Cenozoic. Assuming that a change from sand-dominated sediments in the Palaeocene and Eocene to later mud-dominated sediment corresponds to the change from the erosion of sediment to metamorphic basement, then 1900 – 2400 m average thickness of clastic sediment were present at the start of the Cenozoic, plus any overlying Chalk. This has been subsequently eroded away except along the east and west coasts, where preserved Mesozoic sequences suggest a more extensive original cover. Prior to uplift associated with rifting of the North Atlantic, the Highlands may have been an area of sediment-filled half graben, much like the Inner Hebrides at present day.

Start of main text

Passive margins form a high proportion of all continental margins worldwide, and are the location of often thick sediment sequences which both form a record of the development of the margins and which frequently host commercially important hydrocarbon accumulations. As a consequence, such margins have been intensively studied, especially the margins of the North Atlantic, see for example

Doré et al (2002a) and references therein. One long standing question is the post-rift evolution of such margins – many appear to have been uplifted long after active rifting had ceased (Amidon et al. 2016). Bordering the passive east margin of the North Atlantic, the Scottish Highlands (Fig. 1) form a moderate (c. 1000 m) relief area composed of strata deformed and metamorphosed primarily in the Grampian phase of the Caledonian orogeny (Lambert and McKerrow 1976). The post-orogeny history remains controversial as with many other ancient mountain belts – is the present day topography a relic of the original Caledonian relief (Arkell, 1933; Wills 1951; Ziegler 1990; Bradshaw et al. 1992), exposed continuously since the lower Palaeozoic, or has the area been subsequently uplifted, possibly multiple times (Hall and Bishop, 2002; Holford et al. 2010; Stoker et al. 2010; Stoker et al. 2005b)? Both local and regional phenomena have been proposed as controls on uplift and topography: local effects include igneous intrusion and underplating associated with the rifting of the North Atlantic (White and Lovell 1997; Jones et al. 2002) and small-scale convective flow in the upper mantle (Praeg et al. 2005). Possible regional controls include far-field effects from the Alpine Orogeny (Liu and Galloway 1997) and the Icelandic plume (Jones et al. 2002). Despite the emphatic claim by Judd (1878) that the Highlands were once covered by 4000 – 5000 ft (1200 – 1500 m) of sediment, many workers have followed Arkell (1933) and regarded the Highlands as an uplifted area during the Mesozoic (and indeed since the lower Palaeozoic), supplying sediment to surrounding basins, see discussion by Hudson (2011). However, modern analytical methods have provided an alternative view point: the analysis of apatite fission tracks lead Holford et al. (2010) to suggest that 'significant' thicknesses (c. 2.5 km) of Jurassic rocks may have once covered the Scottish Highlands, which were removed by erosion following uplift in the Cretaceous and Cenozoic. The analysis of apatite fission tracks sometimes identifies uplift or thermal events that are not immediately reconcilable with more traditional geological evidence, leading to an ongoing debate.

It is proposed here that at least part of the Scottish Highlands and the Orkney-Shetland ridge that is topographical the north-eastern extension of the Highlands, hereafter collectively referred to as the Highlands, were at least locally covered by substantial thicknesses of sediment during the Mesozoic as illustrated within the Great Glen by Thomson et al. (1998) for the Kimmeridgian to the Berriasian; and across the Highlands by Holford et al. (2010). Such sediments would have been removed by erosion associated with post-Cretaceous uplift (e.g. Jones et al. 2002) except for in the Hebridean basins to the west and the Moray Firth to the east (Fig. 1). It is here suggested that sediments were deposited in half-graben, developed along reactivated Caledonian faults, filled by the erosion of uplifted footwalls during the Triassic – Jurassic. Hence, during this time, the Highlands may have resembled the present-day Hebrides in terms of topography.

Here, the approach is taken that, if Mesozoic strata were originally deposited upon, and subsequent eroded from, the Highlands, then the resulting sediment must have accumulated in adjacent sedimentary basins, either in the North Sea, or on the Atlantic margin of the UK and Ireland. The stratigraphy of both offshore areas is well established though drilling and seismic surveying for oil exploration (e.g. Ahmadi et al. 2003; Jones et al. 2003; Fyfe et al. 2003), and recent figures are available from the literature for the volumes of most of the relevant stratigraphy (Smallwood 2005; Stoker et al. 2010; White and Lovell 1997; Liu and Galloway 1997). It is therefore possible to estimate the net average thickness of rock that must have been eroded from the pre-Cenozoic Highlands. This leaves the problems of, firstly, how much of this sediment was derived by eroding metamorphic basement, Upper Palaeozoic sediment, and Mesozoic sediment, and secondly how any such sediment was distributed spatially. Here, it is proposed that the change from sand-rich to sand-poor sediment at the end of the Eocene marks the change from the predominant erosion of a sediment cover, to the erosion of the underlying basement. The distribution of the sediment can be constrained by the lack of a plausible source that is external to the study area – hence internal sources are suggested, as uplifted footwalls to extensional faults which also created the accommodation space for the eroded sediments, much as in the preserved basins in the present-day Inner Hebrides.

Geological setting

As above, the metamorphic basement to the Highlands was assembled primarily in the Grampian phase of the Caledonian orogeny, forming part of the Caledonian mountain chain that stretched from Norway into the Appalachian Mountains of the USA. It is overlain unconformably by sediments of Devonian to Cretaceous in age. For the Palaeozoic, substantial thicknesses of Devonian sediment derived from the Caledonian mountain chain are locally preserved, with a cumulative stratigraphic thickness of c. 4500 m in Caithness. This figure may exaggerate the true thickness, which rarely exceeds 2500 m based on geophysical data (Trewin and Hurst 2009). Carboniferous sediments are rare in the Highlands, making any thickness estimate very difficult. However, Carboniferous spores and kaolin are reworked into the Jurassic sediments at Helmsdale so that some sediments must have existed previously (Hillier and Marshall 1992).

The Highlands are surrounded to the North, East and West by sedimentary basins that have been extensively studied, not least as they contain large reserves of hydrocarbons. Similar half-graben basins are exposed in the Inner Hebrides, and on the North-east coast of the Scottish mainland. Within the basins to the east and west of the Scottish mainland maximum thicknesses of Permo-Triassic strata are 1000 – 3000 m and Jurassic strata are 500 – 1500 m (Fyfe et al. 1993). Cretaceous strata are thin (10's m), but may be erosional relics of former thicker sequences (Fyfe et al. 1993). Evidence for the previous existence of Chalk across the Highlands is inevitably restricted to marginal areas such as the thin deposits on the Isle of Arran and Mull (Mortimore et al. 2001) and a 'large volume' of flint contained within the Buchan Gravels Formation on the east side of the Highlands (Merritt et al. 2003) which are now thought to be of Palaeocene-Eocene age based on stable isotope analyses and were plausibly deposited by the rivers that supplied the deep-water marine fan sands of the same age in the Central and Northern North Sea (Hall et al. 2015). These well-documented deep-sea fans e.g. the Andrews Fan (Liu and Galloway 1997; their Fig. 8) are sand-rich and are important oil and gas reservoirs. Anderton (1991) described similar deep sea fans in the Faroe-Shetland Basin. In the North Sea, above the early Eocene Frigg fan, the Westray / Hordaland and Nordland groups are dominated by mudstones except for fringing shallow marine sandstones (Fyfe et al., 2003). The shallowest sediments in the basins surrounding the Highlands are associated with the Pleistocene glaciation (Fyfe et al. 2003). The Cenozoic evolution of the North Sea is well described by Anell et al. (2012).

Methods

The method adopted here is to use literature estimates of the volumes of sediments in basins adjacent to the Highlands, eroded since the start of the Paleocene, and estimates of the areas of erosion, to calculate the average thickness of rock that must have been eroded from the Highlands to supply the sediments. The initial results are presented as thicknesses of solid minerals only, i.e. with zero porosity. This allows for valid comparison of volumes of metamorphic basement, sedimentary rock and unconsolidated sediment. If a rock is a porous sediment, then the gross volume or thickness of the sediment will exceed the cited volume or thickness of the solid component. The porosity-depth relationship of Jones et al. (2002) is used to convert thicknesses of solid rock to thicknesses of sediment – hence all stated sediment thicknesses include porosity.

The rock that was eroded from the Highlands could have been either pre-existing metamorphic basement, or sediment that had been previously deposited upon the basement, i.e. in Devonian to Cretaceous times, hence the average thickness of rock eroded from the Highlands does not provide a direct answer to the question of the presence, or otherwise, of a sediment cover to the pre-Palaeocene Highlands. Here, it is proposed that the change in character of the Cenozoic sediments from the sand-rich Palaeocene-Eocene to the more mudrock-rich post-Eocene is broadly an 'inverse stratigraphy', recording the exhumation of the Scottish basement rocks from below overlying sediments, see discussion of this assumption below.

The volumes of sediment deposited in the UK side of the northern and central North Sea and the corresponding Atlantic margin basins are taken from the literature (Smallwood 2005; Stoker et al. 2010; White and Lovell 1997; Liu and Galloway 1997; Table 1). A volume for the post-Miocene sediments of the North Sea is not available from the literature; maps of sediment distribution in two-way travel time in Anell et al. (2012) suggest that differentiating sediment derived from the Highlands versus that from other areas will be very difficult. A zero value is hence used, so that the calculated mean thickness of sediment eroded from the Highlands is a conservative minimum. The sediment volume estimates for which ranges of values are given in the literature suggest an uncertainty of ± 5000 or 10000 km^3 with no obvious relationship between the uncertainty and the estimate of the volume. A normal distribution with a standard deviation of 3000 is hence assumed for each estimate, such that 95% of the distribution of estimates of volume will lie within ± 6000, and 99% within ± 9000 km^3 of the mean estimated volume. External inputs of sediment have been documented into the Faroe-Shetland Basin, and must be subtracted from the total volume of sediment that has been mapped in the basin, to derive the volume eroded from the Highlands. Contributions of sediment during the Paleocene from a westerly provenance area, i.e. the pre-basalt Faroes Platform terrane or East Greenland, has been estimated as c. 30 % (Smallwood 2008), so that the volume of sediment derived from the Highlands is the total sediment volume reduced by a factor of 0.7. Contributions of sediment from the Rockall Plateau and the Faroe Shelf from earliest Eocene to present–day were estimated to be 46000 km^3 (Andersen et al. 2002). The post-Paleocene sediment volume in the Faroe-Shetland Basin is estimated as c. 147 - 200,000 km^3 (Table 1), so that the contribution from the Rockall Plateau and the Faroe Shelf is 23 - 31 % of the total. As there is no means of determining when, in post-Paleocene times, the sediment was eroded, the assumption has been made that erosion was at a constant rate. Hence, the total volume for each (post-Paleocene) time period has been reduced by a factor of 0.69 – 0.77.

The paleo-land areas that were eroded are not known exactly, as while the maximum possible areas are constrained by the extent of preserved sediment of the appropriate age, it is entirely possible that some sediment has been eroded subsequent to deposition, and that eroded areas were smaller than implied by preserved sediment distributions. Hence, a range of values for the eroded areas (for each time period) are taken. The maximum value for the surface areas of erosion to the west, north and east of the Highlands are constrained by the present-day extent of the preserved sediment, as mapped in the subsurface, for each of the time steps, from Stoker et al. (2010); Ahmadi et al. (2003); Jones et al. (2003) and Fyfe et al. (2003). These maps are imported into ARCGIS which allows surface areas to be measured. The minimum areas of erosion were taken to be bounded by the current coast line to the west, north and south, though with the Shetland and Orkney Islands attached to the mainland as a peninsula rather than as separate islands (Fig. 2). Estimating the position of the southern limits of the eroded areas are more problematic, as little or no sediment of relevant ages is preserved on land, except from the Pleistocene glaciations. As the current drainage pattern of the Highlands is broadly radial, i.e. perpendicular to the coastlines, and previous studies show sediment transport approximately perpendicular to the present day coastline (e.g. Annell et al. 2012, their Fig. 9; Stoker et al. 2010, their Fig. 2), the assumption has been made that post-Cretaceous transport was also approximately perpendicular to the coastlines. Hence, the southern limit of the areas of erosion were drawn from the southern limit of preserved sediment, approximately perpendicular to the present-day coastline (Fig. 2). As the estimated southern limit of the erosional areas for the Eocene, Oligocene and post-Oligocene lie close to the Highland Boundary Fault and its westwards extension, this fault was used as the southern boundary – a conservative assumption which gave slightly larger erosional areas than otherwise, leading to lower estimates of eroded rock thicknesses. The error introduced into the calculations by the uncertainly in the southern limits to the eroded areas is considered to be small.

The average thickness of rock removed from the Highlands during the Cenozoic is then simply the volume of solid sediment divided by the eroded surface area, computed for each epoch using a Monte-Carlo routine written in the R-language. This method allows for the calculation of eroded thicknesses despite the high uncertainty in all of the input parameters – a single 'best estimate' thickness might be misleading. Input parameters (Table 1) are taken to be normally distributed for erosional area and sediment volume, but uniformly distributed for the proportion of sediment contributed from the Rockall Plateau and the Faroe Shelf, as above, and the eroded surface area.

The number of iterations (10^6) was chosen to ensure that there was no significant variation between individual runs. Average erosion rate for each time period was calculated by dividing the sediment volume by the duration of erosion, also using the Monte Carlo method. This does not imply that the rate of erosion is thought to have been constant during any time period. The main advantage of the Monte Carlo method is that it can deal with uncertainty in multiple input parameters – for example, oil companies routinely use the method to estimate volumes of reserves, producing probabilistic distributions of reserves rather than single values. The method provides a better estimate of uncertainty than choosing 'best' or central values and uncertainty ranges.

Results

The calculated thickness of rock (as solid volume, i.e. with zero porosity) eroded from the Highlands during the Cenozoic is shown in Table 2 (quartiles) and Figure 3 as probability density functions, and the total ranges from c. 1700 - 3000 m. The most probable values are in the 2000 – 2400 m range (2nd and 3rd quartiles). Figure 4 shows the cumulative eroded thickness for the entire Cenozoic. Figure 5 shows calculated erosion rate through the Cenozoic, with the highest rates in the Palaeocene. Note that there is no curve for the Pliocene to Recent as there is no published estimate of the volume of sediment of this age in the North Sea.

Discussion – the Cenozoic uplift history of the Highlands

Estimate of Cenozoic erosion

The average thickness of rock removed from the Highlands in the Cenozoic, as calculated here, is a little higher than past estimates. Hall (1991) used a similar technique to calculate an average thickness of 908 m, while Jones et al. (2002) suggested a range of 0.5 to 2 km based on a combination of apatite fission track analysis and basin modelling. The higher thicknesses of eroded rock derived here compared to that of Hall (1991) is the result of more recent estimates of offshore sediment volumes, which were not previously available. A possible source of error in the calculations presented here is from sediment that was deposited in the offshore basins that was not derived from the Highlands, but from adjacent areas, e.g. from Norway for the North Sea, or the Rockall

Plateau and the Faroe Shelf. The latter areas were considered in the Methods section, and a correction to the sediment volumes has been made. For the North Sea, Anell et al. (2012) show sediment transport directions derived from seismic progradation patterns. For the Paleogene, sediment transport is approximately perpendicular to the modern shoreline, at least for the margin of the Highlands which is of interest here. There is no evidence for significant axial transport within the North Sea, or for the derivation of sediment from further south. Furthermore, Anell et al. (2012) specifically link depositional centres in the North Sea to source areas (their Fig. 9, from Huuse et al. 2001 and Jordt et al. 2000) which demonstrates that the Paleogene deep water fans and the Neogene sediments included in our estimates were indeed derived from the Highlands.

Did sediments cover the Highlands before the Paleocene?

The sediments in the basins surrounding the Highlands could have been derived by the erosion of metamorphic basement or from a pre-existing sediment cover. Morton (1984) noted that at least some of the Palaeocene sandstones contain significant quantities of unstable epidote and hornblende and are plausibly derived directly from basement, though could be from unidentified intermediate sediments. It is noteworthy that the epidote and hornblende component of the heavy mineral assemblage are dissolved by present-day burial depths of between 600 and 1200 m, suggesting that, if these sediments were part of a previous sedimentary cover, then they were only previously buried to relatively shallow depths. Sediment in which the unstable minerals are absent were thought to have been derived via intermediate sediments, most plausibly of Jurassic age (Morton 1984). Heavy mineral data are not available from the post-Palaeocene of the North Sea, or the Atlantic margin sediments.

The deep marine sediment fans of the North Sea become smaller and less common throughout the Cenozoic, with a similar (if not identical) pattern of a very sand-rich Paleocene and Eocene in the Faroe-Shetland Basin (Anderton 1993; Lamers and Carmichael 1999). White and Lovell (1997) argued that the Paleogene sediment fans of the North Sea correlate with pulses of uplift of the Scottish mainland, caused by episodes of volcanic activity on the west coast of Scotland. While calculated erosion rates are undoubtedly high during the Palaeocene compared to the remainder of the pre-glacial Cenozoic (Fig. 5), it is here argued that rapid erosion rates do not inherently lead to more sand-rich sediment than lower erosion rates. It could be argued that higher erosion rates, associated with uplift and forced regression, might move sand further into a basin, i.e. into the deep waters in which the fan sands of the Paleocene and Eocene where deposited. However, the contrast between the Paleocene / Eocene and later deposits is not the spatial position of sands, but the proportions of sand versus finer grained sediments (Liu and Galloway, their Fig. 5).

Instead, it is here suggested that the sands of the deep sea fans represent the erosion of sand-rich precursor sediment, and that the more mud-rich Oligo-Miocene sediments of the North Sea are derived directly from the metamorphic basement that is exposed at the present day (along with subordinate Palaeozoic sediments). These sand-rich precursor sediments are still ultimately derived by eroding metamorphic basement, but the first-cycle transport and depositional processes concentrated the sand fractions close to the source areas, while removing the finer fractions to more distal locations largely out with the Highland area. Hence, it is proposed that the change in character of the Cenozoic sediments from the sand-rich Palaeocene-Eocene to the more mudrock-rich post-Eocene is broadly an 'inverse stratigraphy', recording the exhumation of the Scottish basement rocks from below overlying sediments. The calculated average thickness of the restored, combined Palaeocene plus Eocene strata is 1200 – 1600 m (2nd and 3rd quartiles, Fig. 4) with zero porosity. Using the porosity-depth relationship of Jones et al. (2002), the thickness as porous sediment becomes 1900 – 2400 m. This is proposed as the best estimate of the average thickness of clastic sediment eroded from the Highland area in the Cenozoic. These are average figures, and clearly the sediment is unlikely to have been distributed uniformly over the area. The average thickness of sediment eroded that is calculated here is comparable to the preserved thickness of sediment within the basins to the east and west of the Scottish mainland. It is also compatible with the suggestion of Holford et al. (2010) that 'significant thicknesses' of Jurassic strata had previously covered the Highlands, perhaps 2 – 3km.

Supporting evidence for a sediment cover over the Highland basement rocks can be gained from the thermal maturity of preserved sediments. Vitrinite reflectance is high in Caithness (R_o = 2-3 %) and in Orkney (1 – 1.5%; Hillier and Marshall, 1992), compared to values away from known igneous intrusions in NW Scotland (< 1 %; Bishop and Abbott, 1995; their Fig. 2). Hillier and Marshall (1992) suggest minimum paleo-temperatures of 100 - 120 °C, implying the erosion of 'more than 2 – 3 km of cover' or a geothermal gradient much greater than 40 °C/km. The calculated thickness of sediment eroded is similar to the 1.55 km of early Cenozoic erosion of NW England, effectively exhuming the topography of what is now the Lake District (Green et al. 2002). This figure was derived from samples with a range of elevations that allowed paleo-geothermal gradients to be measured (rather than assumed) and effectively supersedes earlier estimates of erosion, some of which are significantly higher, e.g. the 3km of Lewis et al. (1992).

The age and source of any previous sediment cover

If 1900 – 2400 m average thickness of sediments were present over the Highlands at the start of the Cainozoic, what age were they and from where were they derived? The sediments could have been Mesozoic, or post-Caledonian Palaeozoic in age. As above, all of Devonian, Permo-Triassic and Jurassic sediments are present in significant thickness in basins surrounding the Highlands – only Carboniferous and Cretaceous sediments are absent in significant thicknesses. It seems probable that strata of all the former ages would have occurred at least locally overlying the Caledonian basement, although the analysis presented here does not provide an independent assessment of the age distribution. However, Morton (1984) considered that such sediments were most plausibly of Jurassic age, and Holford et al. (2010) provided apatite fission track data interpreted as evidence for a Jurassic sediment cover of c. 2.5 km thickness. We therefore follow these authors, and indeed Judd (1878), in arguing that the previous existence of significant volumes of Jurassic sediments over the Highlands is at least consistent with the available evidence. Importantly, there is strong evidence against a continuous blanket covering of sediment across the Highlands at this time (e.g. Hudson 2011), for example the proximal sand-rich sediments in the Jurassic of the Inner Hebrides which must have been derived from nearby land. Hence a uniform blanket of sediment cover is not a feasible geometry for the sediment, but local accumulations in fault-controlled extensional basins is consistent with the likely derivation of any Jurassic age sediments, and with known tectonic styles, as follows.

If the postulated sedimentary cover to the Highlands was post-Devonian, then from where was it derived? As a large volume of sediment is involved (c. 186,000 km^3 solid volume; Table 1) then a significant erosion event is implied. During the Jurassic, the uplift of the mid-North Sea dome generated 70 - 80,000 km^3 of sediment (including porosity) assuming 400 – 500 m of vertical erosion (lower Jurassic only), and a radius of 400 km (data from Underhill and Partington 1993). This is only a fraction of the required volume of sediment, as above, and in any case at least some of the eroded sediment was probably deposited in the middle Jurassic Brent Group of the North Sea, and the

Yorkshire area of England to the south. Northern England, to the south of the Highlands, was also uplifted as part of the mid-North Sea dome, and any contribution from here is hence included in the figure above. The large-scale uplift and erosion of Northern England documented by Green et al. (2002) is too late to have contributed to Jurassic or earlier sedimentation. Sediment could presumably not have been derived from East Greenland to the north-west, as the Rhaetian – Early Bajocian thermal subsidence, and the onset of rifting in the Late Bajocian (Surlyk 2003) would have isolated the Highlands from the eroding Greenland craton. Hence the most likely source area is the Highlands itself – eroded crestal areas of uplifted fault blocks supplying sediment to areas of hanging wall subsidence, as suggested for the Permo-Triassic strata of the Hebrides by Steel and Wilson (1975).

It has been previously suggested that at least some of the Highlands may have been traversed by a series of faults of Caledonian origin that were active during the Mesozoic (Roberts and Holdsworth 1999). As proof that some of these large faults are very long lived, Le Breton et al. (2013) recorded evidence for right-lateral movement of the Great Glen Fault during the Cenozoic, related to left-lateral slip along the Faroe Fracture Zone which caused a period of uplift and exhumation in Scotland. Here we propose that Mesozoic movement of faults of originally Caledonian age may have generated half-graben that filled with sediment derived from Highland basement lithologies eroded from the uplifted footwalls. This is consistent with the surviving half-graben of the Inner Hebrides, where sediment supply was plausibly from local sources, i.e. the Highland metamorphic basement and to a lesser extent the Lewisian (Hudson and Andrews 1987). It is also consistent with the well-documented evidence for late- Jurassic rifting in the Moray Firth (Pickering, 1984) and the wider North Sea area. The pre-Cenozoic Highlands may hence have resembled the present day series of half-graben and uplifted footwalls of the Inner Hebrides, or indeed the similar structures buried beneath younger sediments in the North Sea to the east. Differential Cenozoic uplift elevated the half-graben that are now sited on the Scottish mainland, resulting in their destruction by erosion but preserving those in the Hebrides and in the North Sea.

Controls on uplift

With the possible exception of the Pleistocene glaciation, erosion and presumably uplift of the Highlands was most rapid in the Palaeocene (Fig. 5). White and Lovell (1997) suggested that this uplift was most severe on the west coast, where the Palaeocene volcanism is concentrated, yet this is where Jurassic basins are preserved at present day. If Cenozoic uplift and erosion were concentrated here, then very substantial thicknesses of sediment would have to be removed to supply all the known Palaeocene and Eocene sediment preserved in surrounding basins. That such thicknesses have not been removed is suggested by the low degree of lithification of the preserved Jurassic sediments in the Inner Hebrides (Hudson and Andrews, 1987), which would have had to have been buried to substantial depths under the hypothetical eroded sediment. This implies that the maximum uplift was not in the Hebrides close to the surface volcanism, but further east as calculated by Jones et al. (2002). This is consistent with Holford et al. (2010), whose samples from the west coast of Scotland recorded cooling only around contemporaneous igneous intrusions at this time.

The controls on the topography of both passive margins and ancient orogenic belts are still poorly understood (Amidon et al. 2016), though there are multiple contender processes. The hypothesis that the Highlands are a relic of the original Caledonian topography is inconsistent with apatite fission track data (Holford et al. 2010; Doré et al. 2002b) which indicates multiple episodes of uplift and burial. This conclusion has also been drawn for at least portions of the Appalachian Mountains (USA; McKeon et al. 2014), and for the Lake District of England which was apparently eroded to below sea level by the early Carboniferous (Guion et al., 2000, their Figure 14.2). Both these areas are the lateral equivalents of the Highlands in the sense that they also formed as a result of the closure of the lower Palaeozoic Iapetus Ocean. The early Cenozoic uplift of the Highlands, recorded both as a significantly increased erosion rate (Liu and Galloway, 1997; Fig. 5) and as apatite fission track data (Holford et al. 2010), can be interpreted as a consequence of the rifting of the North Atlantic, plausibly a consequence of local underplating as proposed by White and Lovell (1997). Thermal subsidence modelling suggests only between 0.5 and 2 km maximum of denudation should have occurred across the majority of Scotland during the Cenozoic (Jones et al. 2002), implying that other uplift processes have been active.

The cause of uplift after the initial rifting of the north Atlantic could include far-field effects from the Alpine Orogeny (Liu and Galloway 1997) and the Icelandic plume (Jones et al. 2002), or changing forms of small-scale convective flow in the upper mantle (Praeg et al. 2005). These processes may have driven the uplift episodes at 45 – 20 Ma and 15 – 10 Ma identified by Holford et al. (2010), though it is noticeable that the average erosion rate of the Highlands during this time is only slightly higher than the long-term average for the Appalachian Mountains (c. 20 m / Ma; McKeon et al. 2014; compare to Fig. 5). The higher resolution erosion rates calculated by Liu and Galloway (1997) do show a broad increase in erosion at approximately 45–20 Ma and possibly at c. 10 Ma, which could be cited as supporting evidence. Uplift of the Highlands might have also been expected during the enhanced erosion of the Pleistocene glaciation, though the data of Holford et al. (2010) do not apparently show this. Such intense erosion causes net uplift as deep valleys are cut into the landscape causing crustal thinning (Huuse, 2002). Instead, Stoker et al. (2005a) record uplift-driven sedimentation beginning from c. 4 Ma on the Atlantic margin between the UK and Norway. At present the timing and cause of uplift and subsidence of 'passive' margins appears complex (Stoker et al. 2005b).

Conclusions

A volume-balance of sediment derived from the Scottish Highlands and Orkney-Shetland ridge during the Cenozoic suggests that 1900 – 2400 m of post-Caledonian sediment could have been eroded during this interval, plus any covering of Chalk. Previously published analysis of apatite fission track distributions lead to a similar conclusion (Holford et al. 2010). That a significant sediment cover existed locally is demonstrated by the thermal maturity and thickness of preserved sediment around the margins of the Highlands, and potentially by the 'inverted stratigraphy' of the derived sediments – sand-rich in the Paleocene and Eocene from pre-existing sediment, but more muddy subsequently derived directly by eroding metamorphic basement. It is here suggested that across the Highlands, sediments were deposited in half-graben, developed along reactivated Caledonian faults. In the absence of a plausible external sediment source after the initial erosion of the Caledonian mountain chain, the graben were filled by the erosion of uplifted footwalls most plausibly during the Triassic - Jurassic, when the Highlands may have resembled the present-day Hebrides in terms of topography. Cenozoic uplift and erosion were not uniform, but preferential uplift of the centre of the Highlands resulted in the entire removal of a sediment cover which was, in contrast, preserved on both coastlines as the fills of half graben.

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Figure Captions, Wilkinson

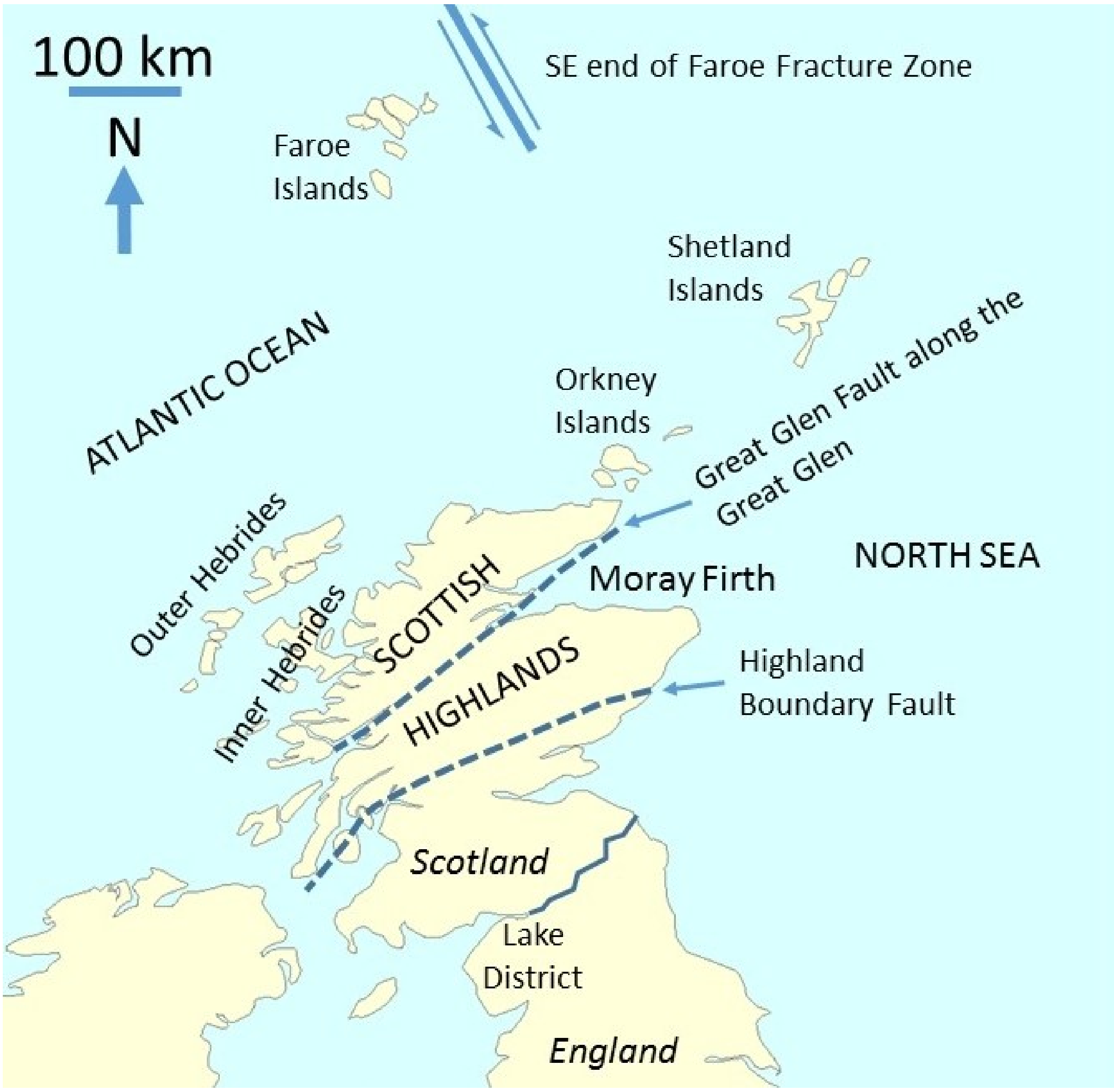

Fig. 1. Location map.

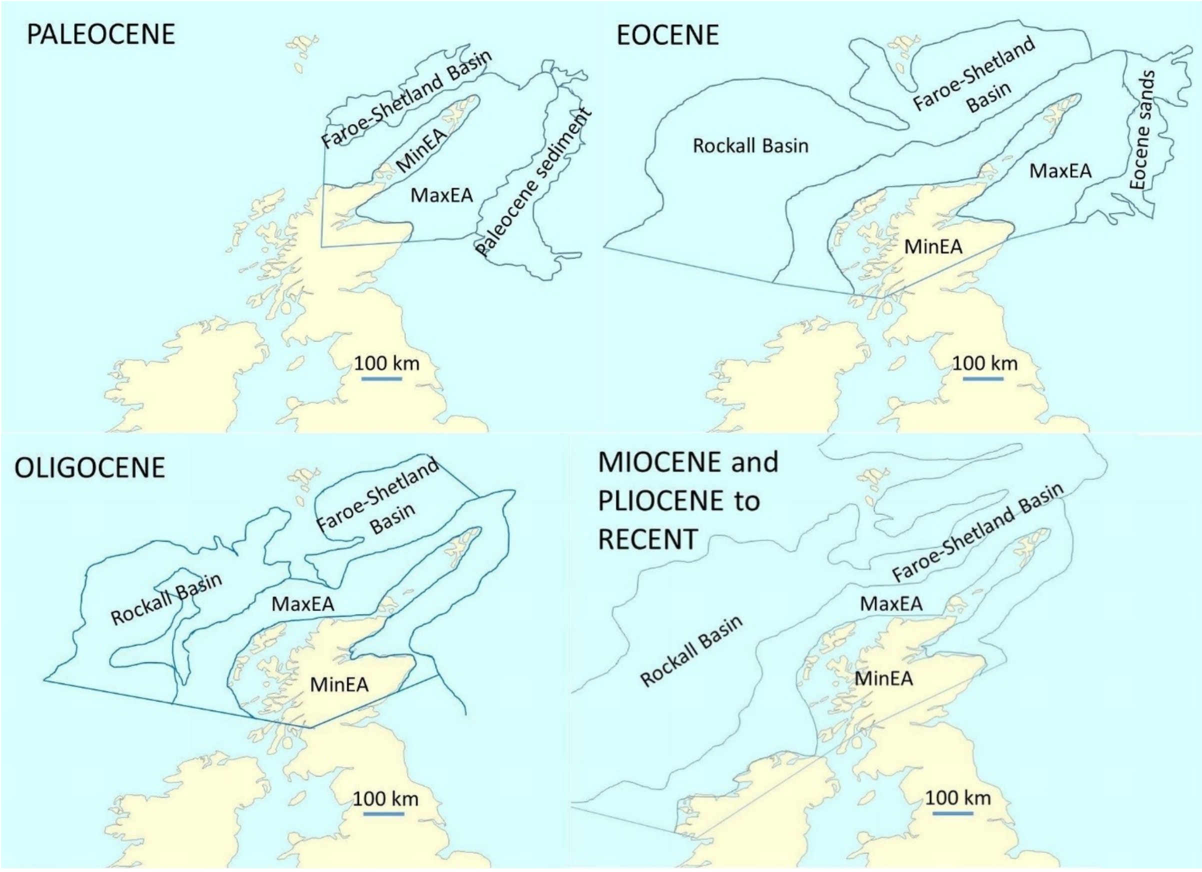

Fig. 2 Maps of sediments and erosional areas. MinEA is the minimum estimated area of erosion, MaxEA is the maximum area, see text for sources.

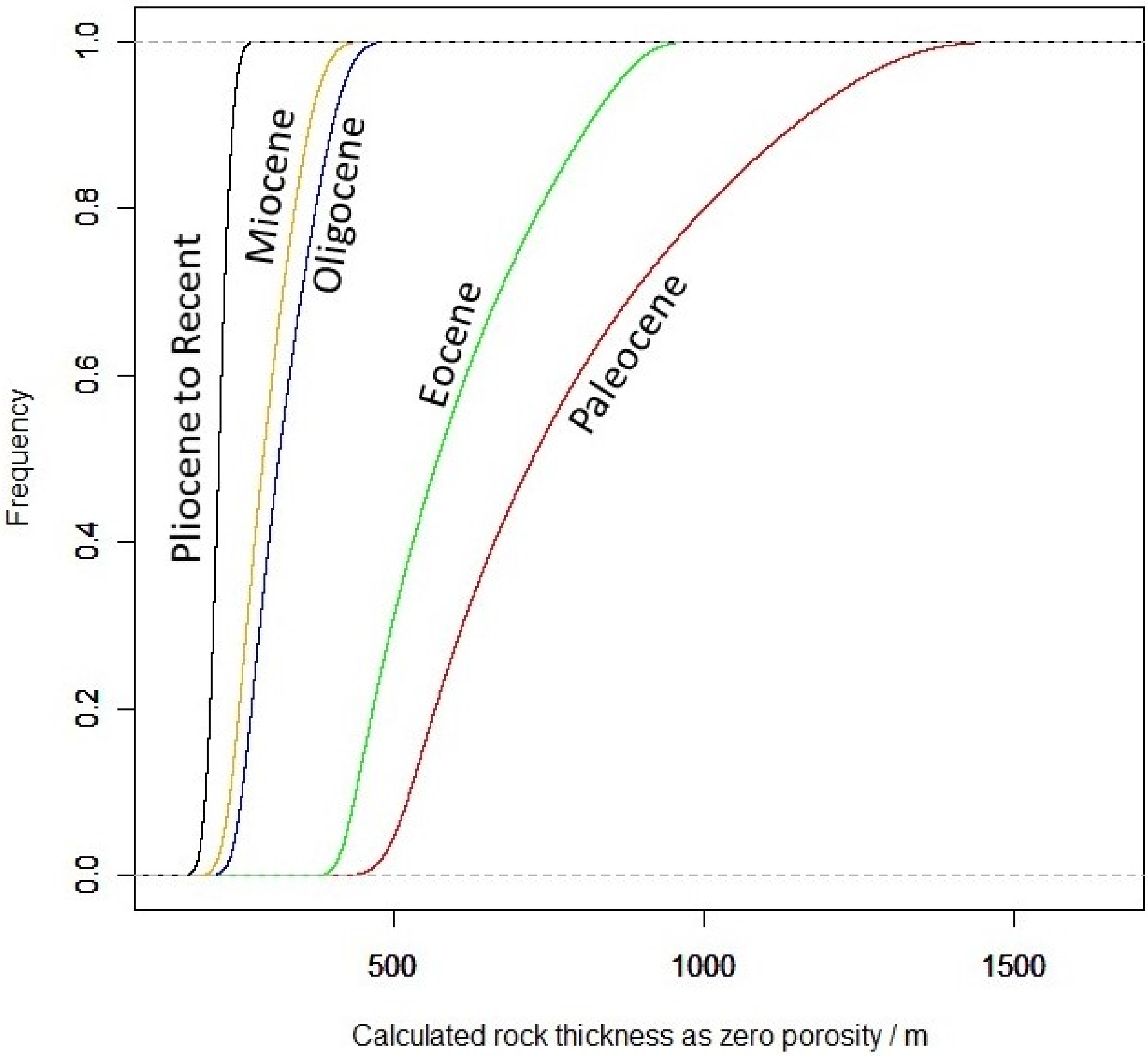

Fig. 3. Calculated thickness of rock (zero porosity) eroded from the Highlands during the Cenozoic, by epoch.

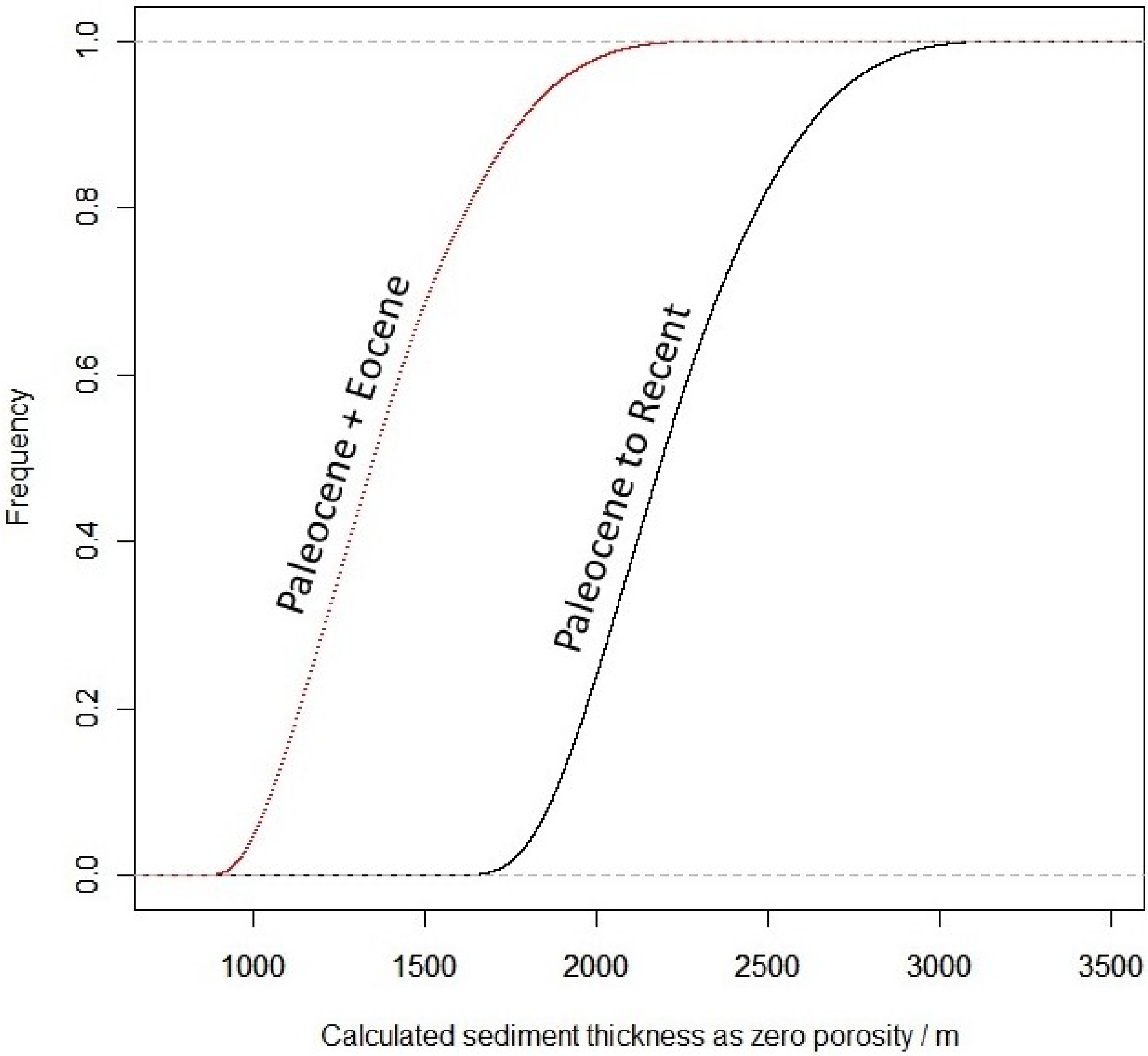

Fig. 4. Calculated average thickness of rock (zero porosity) eroded from the Highlands during the entire Cenozoic and during the Paleocene plus Eocene, the latter is here assumed to be largely derived by eroding pre-exiting sediment and hence sand-rich.

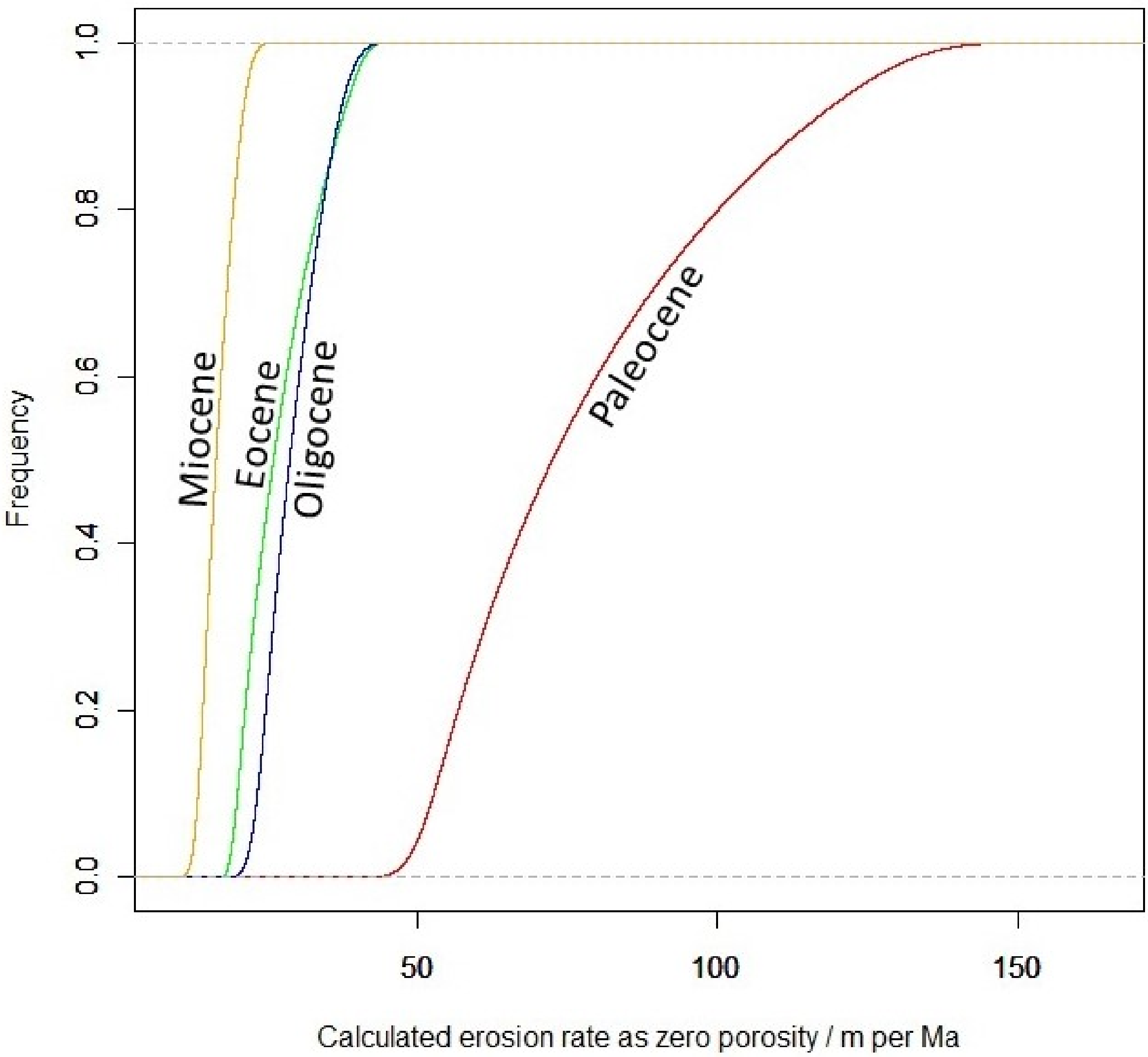

Fig. 5. Calculated average erosion rates through the Cenozoic, assumes zero-porosity in the eroded strata.

Table 1 – Literature and input data (**bold**) for MonteCarlo calculations of eroded sediment thicknesses and erosion rates

Epoch	Paleocene	Eocene	Oligocene	Miocene	Pliocene to Recent
Minimum eroded area / km^2	**45000**	**105000**	**132000**	**140000**	**144000**
Maximum eroded area / km^2	**122000**	**230000**	**227000**	**231000**	**156000**
FSB volume / km^3 Stoker et al. (2010)	-	57500 - 76800	16300 - 22500	35100 - 48800	37900 - 52100
FSB volume / km^3 Smallwood (2005, 08)	35 – 55000	48000			
FSB volume / km^3	**45000**	**60000**	**20000**	**45000**	**45000**
FSB SD / km^3	**3000**	**3000**	**3000**	**3000**	**3000**
FSB reduction factor (see text)	**0.7**	**0.69 – 0.77**	**0.69 – 0.77**	**0.69 – 0.77**	**0.69 – 0.77**
North Sea volume / km^3 White and Lovell (1997)	25195 (excludes Balder fan as Eocene)	-	-	-	-
North Sea volume / km^3 Liu and Galloway (1997)	33042 (excludes Chalk)	51598	41502	21400	-
North Sea volume / km^3	**29000**	**52000**	**42000**	**21000**	**0**[a]
North Sea SD / km^3	**3000**	**3000**	**3000**	**3000**	**-**

[a] No literature volume available, see text; SD = standard deviation; FSB = Faroe-Shetland Basin

Table 2 – Calculated thickness of eroded rock (zero porosity) by epoch and the Cenozoic as quartiles.

	Q_{25}	Q_{50}	Q_{75}
Plio-Pleistocene*	190	210	230
Miocene	260	290	330
Oligocene	280	320	360
Eocene	480	570	700
Palaeocene	590	720	940
Palaeocene + Eocene	1200	1350	1600
Total Cenozoic	2000	2200	2400

* uses data from Faroe-Shetland Basin only